

MICROLENSING IMPLICATIONS FOR HALO DARK MATTER

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The observations of microlensing events in the Large Magellanic Cloud suggest that a sizable fraction ($\sim 50\%$) of the galactic halo is in the form of MACHOs (Massive Astrophysical Compact Halo Objects) with an average mass $\sim 0.27M_{\odot}$, assuming a standard spherical halo model. We describe a scenario in which dark clusters of MACHOs and cold molecular clouds (mainly of H_2) naturally form in the halo at galactocentric distances larger than 10–20 kpc.

1 Introduction

A central problem in astrophysics concerns the nature of the dark matter in galactic halos, whose presence is implied by the flat rotation curves in spiral galaxies. As first proposed by Paczyński¹, gravitational microlensing can provide a decisive answer to that question², and since 1993 this dream has started to become a reality with the detection of several microlensing events towards the Large Magellanic Cloud^{3,4}. Today, although the evidence for MACHOs is firm, the implications of this discovery crucially depend on the assumed galactic model. It has become customary to take the standard spherical halo model as a baseline for comparison. Within this model, the average mass reported by the MACHO team is $0.5^{+0.3}_{-0.2} M_{\odot}$, which is based upon their first two years data³. The inferred optical depth is $\tau = 2.1^{+1.1}_{-0.7} \times 10^{-7}$ when considering 6 events^b (or $\tau = 2.9^{+1.4}_{-0.9} \times 10^{-7}$ when considering all the 8 detected events). Correspondingly, this implies that about 45% (50% respectively) of the halo dark matter is in form of MACHOs assuming a standard spherical halo model.

Instead, using the mass moment method yields an average MACHO mass⁵ of $0.27 M_{\odot}$. Unfortunately, because of the presently available limited statistics different data-analysis procedures lead to results which are only marginally consistent. Apart from the low-statistics problem – which will automatically disappear from future larger data samples – we feel that the real question is whether the standard spherical halo model correctly describes our galaxy⁶. Besides the observational evidence that spiral galaxies generally have flattened halos, recent determinations of the disk scale length, the magnitude and slope of the rotation at the solar position indicate that our galaxy is best described by the maximal disk model, which implies a minimal halo model. This conclusion is further strengthened by the microlensing results towards the galactic centre, which imply that the bulge is more massive

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^bIn fact, the two disregarded events are a binary lensing and one which is rated as marginal.

than previously thought. For such halo models the expected average MACHO mass should be smaller than within the standard halo model. Indeed, a value $\sim 0.1 M_{\odot}$ looks as the most realistic estimate to date and suggests that MACHOs are brown dwarfs.

2 Mass moment method

The most appropriate way to compute the average mass and other important properties of MACHOs is to use the method of mass moments developed by De Rújula et al.⁷. The mass moments $\langle \mu^m \rangle$ are related to $\langle \tau^n \rangle = \sum_{events} \tau^n$, with $\tau \equiv (v_H/r_E)T$, as constructed from the observations ($v_H = 210 \text{ km s}^{-1}$, $r_E = 3.17 \times 10^9 \text{ km}$ and T is the duration of an event in days). We consider only 6 (see footnote *b*) out of the 8 events observed by the MACHO group during their first two years^c. The ensuing mean mass is $\langle \mu^1 \rangle / \langle \mu^0 \rangle = 0.27 M_{\odot}$, assuming a standard spherical halo model. When taking for the duration T the values corrected for “blending”, we get as average mass $0.34 M_{\odot}$. Although this value is marginally consistent with the result of the MACHO team, it definitely favours a lower average MACHO mass.

For the fraction of the local dark mass density detected in the form of MACHOs, we find $f \sim 0.54$, which compares quite well with the corresponding value ($f \sim 0.45$) calculated by the MACHO group in a different way. However, the uncertainties on f are large, due to the lack of precise knowledge on the actual shape of the dark halo and its total mass.

3 Formation of dark clusters

A major problem concerns the formation of MACHOs, as well as the nature of the remaining amount of dark matter in the galactic halo. We feel it hard to conceive a formation mechanism which transforms with 100% efficiency hydrogen and helium gas into MACHOs. Therefore, we expect that also cold clouds (mainly of H_2) should be present in the galactic halo. Recently, we have proposed a scenario^{9,10,11,12,13} in which dark clusters of MACHOs and cold molecular clouds naturally form in the halo at galactocentric distances larger than 10–20 kpc, with the relative abundance possibly depending on the distance.

The evolution of the primordial proto globular cluster clouds (which make up the proto-galaxy) is expected to be very different in the inner and outer parts of the Galaxy, depending on the decreasing ultraviolet flux (UV) from the centre as the galactocentric distance R increases. In fact, in the outer halo no substantial H_2 depletion should take place, owing to the distance suppression of the UV flux. Therefore, the clouds cool and fragment - the process stops when the fragment mass becomes $\sim 10^{-2} - 10^{-1} M_{\odot}$. In this way dark clusters should form, which contain brown dwarfs and also cold H_2 self-gravitating cloud, along with some residual diffuse gas (the amount of diffuse gas inside a dark cluster has to be low, for otherwise it would have been observed in the radio band).

^cIn the meantime the MACHO group has found at least six additional events towards the LMC and at least one towards the SMC⁸. These data are, however, not yet fully analyzed.

We have also considered several observational tests for our model^{9,14}. In particular, a signature for the presence of molecular clouds in the galactic halo should be a γ -ray flux produced in the scattering of high-energy cosmic-ray protons on H_2 . As a matter of fact, an essential information is the knowledge of the cosmic ray flux in the halo. Unfortunately, this quantity is unknown and the only available information comes from theoretical considerations. Nevertheless, we can make an estimate of the expected γ -ray flux and the best chance to detect it is provided by observations at high galactic latitude. Accordingly, we find a γ -ray flux (for $E_\gamma > 100$ MeV) $\Phi_\gamma(90^\circ) \simeq \tilde{f} (0.4 - 1.8) \times 10^{-5}$ photons $\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$ (\tilde{f} stands for the fraction of halo dark matter in the form of gas), if the cosmic rays are confined in the galactic halo, otherwise, if they are confined in the local galaxy group¹⁵ $\Phi_\gamma(90^\circ) \simeq \tilde{f} (0.6 - 3) \times 10^{-7}$ photons $\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$. These values should be compared with the measured flux by the SAS-II satellite for the diffuse background of $(0.7 - 2.3) \times 10^{-5}$ photons $\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$ or the corresponding flux found by EGRET of $\sim 1.1 \times 10^{-5}$ photons $\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$. Thus, there is at present no contradiction with observations. Furthermore, an improvement of sensitivity for the next generation of γ -ray detectors will allow to clarify the origin of this flux or yield more stringent limits on \tilde{f} .

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